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The Europa Orbiter Mission Design

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Abstract

The Europa Orbiter mission is planned to be the first in NASA's Outer Planets/Solar Probe Program. Following on the heels of the successful *Galileo* mission, which provided dramatic evidence that a water ocean existed on Europa at least in the recent past, the primary goal of Europa Orbiter is to ascertain whether or not a subsurface ocean of water exists today. The reference mission profile emerged from a series of studies of various mission options; only the 2003 direct mission is described in detail. The key mission design challenges, including managing radiation dose and ΔV, motivates the mission profile, which culminates in a one month mission around Europa. The use of automated navigation techniques during the final approach to Europa is expected to reduce operations cost and to reduce the ΔV required to enter Europan orbit. A brief description of the programmatic considerations, science objectives and current status of the flight system is included for background.

Introduction

Although *Voyager 2* only came within 204,000 km of Europa, and *Voyager 1* several times farther, images they sent back strongly suggested Europa had an unusually young surface. Recent *Galileo* observations of Europa have added a vast amount of evidence to support and extend that interpretation, including clear indications of flow-like features and erupted material, lack of impact cratering, significant geologic activity, and tectonic activity that repeatedly overlaps earlier tectonic activity,[1-5] floe-like structures that can be translated and rotated to fit together like a jigsaw puzzle,[6] evidence of non-synchronous rotation,[7] non-ice materials on the surface associated with crack-like features,[8] magnetic field signatures that are consistent with a ~100 km conducting shell (with conductivity similar to that of sea water)[9], and perhaps the most tantalizing of all, apparent "icebergs" now frozen in place.[10] Such evidence has elevated Europa to one of the highest target priorities for Solar System exploration, as it may be the only place in the Solar System other than Earth that may have vast liquid water oceans.

The Outer Planets/Solar Probe Program, slated for formal go-ahead in FY2000, has planned as its first mission the Europa Orbiter (EO). This program is planned to be an ongoing exploration of the outer Solar System, with a mission to Pluto currently scheduled second, and a mission to the Sun, Solar Probe, its third mission. This may seem at first an odd combination, but the missions are unified through the shared development of key flight system technologies (such as the power system, transponder, software, and avionics), operational philosophies and mission control.

The current project plan calls for the launch of Europa Orbiter in November 2003, Pluto-Kuiper Express (PKE) in December 2004, and Solar Probe in February 2007. The opportunity to switch the launch order of EO and PKE, however, is a key requirement of the program readiness strategy. If the option to switch the order of the PKE and EO launches is exercised, the PKE launch would be moved up to November 2003 and EO would move into the December 2004 slot.

Science Objectives

The Europa Orbiter Science Definition Team (SDT) has recommended a minimum set of objectives that must be met in order for the mission to be scientifically viable.[11] It is this set of objectives that drives the flight system and mission design. They are:

1A) Objectives

1) Determine the presence or absence of a subsurface ocean
2) Characterize the 3-D distribution of any subsurface liquid water and its overlying ice layers
3) Understand the formation of surface features including sites of recent or current activity, and identify candidate sites for future lander misions

Additionally, the SDT defined a set of important secondary objectives that "are of high scientific importance, but not so critical for this mission as to fall within the irreducible baseline".[11]

1B) Objectives

1) Characterize surface composition, especially compounds of interest to pre-biotic chemistry
2) Map the distribution of important constituents on the surface
3) Characterize the radiation environment in order to reduce uncertainties for future missions, especially landers

The SDT identified a strawman set of investigations which would satisfy the 1A objectives. The strawman set includes gravity field mapping using the spacecraft transponder, a laser altimeter, an ice penetrating radar sounder, and imaging.

Flight System Overview

A recent concept for the flight system for EO is shown in Figure 1. It is important to note that the project is still at an early stage of planning and many significant characteristics of the design will likely change between now and launch.

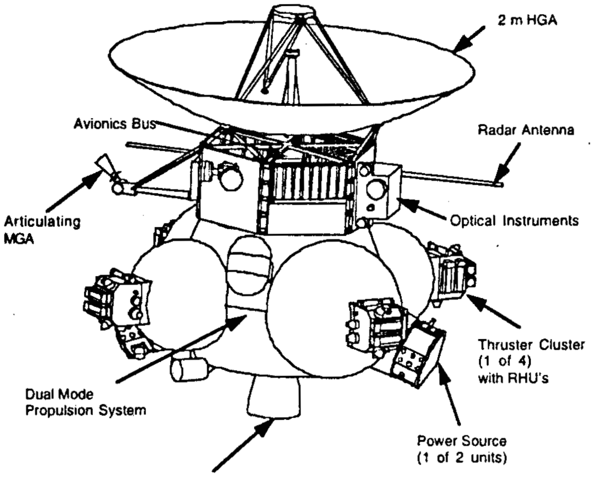
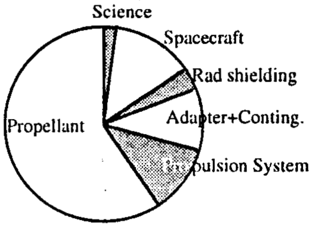


Figure 1. Europa Orbiter Conceptual Design

The reference spacecraft is dominated by the large, dual-mode propulsion system, sized to provide the mission's 2500 m/s ΔV requirement. Attitude control in this concept would be provided by 22N, 0.9N, and milli-N thrusters, the latter two in couples. In this design, the spacecraft would be powered by a radioisotope power source which delivers a total of 150 W at end-of-mission. The body-mounted high-gain antenna shown is 2m in diameter, and in concert with the rest of the telecom system, supports a downlink data rate of 20kbps from 5 AU at X-band to a 70m station. A medium-gain antenna is mounted on struts and is articulated to provide radiometric tracking data for orbit determination while the altimeter is nadir pointed. All the instruments are body mounted, including the radar antenna, which may span 10-15 meters from tip-to-tip (not shown in its full deployment). Spacecraft control and initial science data processing is performed by a redundant, radiation-hardened processor running at 100 MIPS. About 4 Gbits of non-volatile memory are expected to be available for science data storage.



MASS BREAKDOWN:

Science	20 kg
Spacecraft	130 kg
Rad shielding	31 kg
Adapter+Conting.	99 kg
Propulsion System	105 kg
Propellant	565 kg

Figure 2. Propellant and Propulsion Make Up 70% of EO's Mass

Figure 2 provides a breakdown of the spacecraft mass.

Launch/Interplanetary Trajectory/Arrival Strategy

The EO reference mission calls for an STS/IUS/Star48V launch during a 21-day launch period extending from 8-November-2003 through 28-November-2003. Figure 3 defines the major mission phases. The spacecraft will take a direct trajectory to Jupiter (see Figure 4), arriving between July 2006 and August 2007 (depending on launch date). The variable arrival day strategy allows the C_3 to be held to 80 km^2/s^2, to which the launch vehicle can inject 980 kg (after a 10% reserve has been removed).

Because of the planetary geometry at the times of launch and arrival, a broken plane ma-

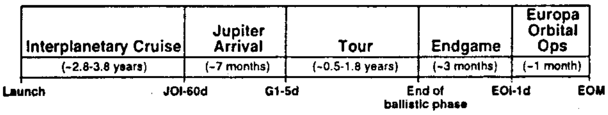


Figure 3. Mission Phases

neuver is required about 9 months after launch. Figure 5 shows how the broken plane maneuver (BPM), Jupiter orbit insertion (JOI) and perijove raise (PJR) vary across the launch/arrival space. The BPM varies in magnitude from about 270 m/s near the start of the launch period to nearly zero at the end of the launch period. This offsets the rise in JOI magnitude due to higher V-infinity for later arrival dates (see also Table 1).

Jupiter Arrival/Initial Orbit

When the EO mission was initially conceived,[12] the capture at Jupiter involved a JOI burn made at a perijove range of only 1.02 R_J (i.e., at 1.02 times the radius of Jupiter) following a close flyby of Io inbound, leading to a 200 day initial orbit about Jupiter. After a perijove raise maneuver, the spacecraft would return to Ganymede (G1). This very low perijove was selected in order to minimize JOI, although it was recognized that such a low perijove might provide special difficulties associated with the ring plane crossing, finite burn losses at the JOI burn due to a rapidly changing flight path angle, and the high radiation environment.

Additional work to study the relative merits of a Ganymede flyby versus an Io flyby before perijove and the effect on ring plane crossing distance and total ΔV of varying the initial perijove range revealed the existence of relative minima for both Io and Ganymede trajectories which were only slightly more costly than performing JOI at the 1.02 R_J value. Figure 6 compares the separate ΔV values for the broken plane maneuver (BPM), Jupiter orbit insertion maneuver (JOI) and perijove raise maneuver (PJR), and their combined total for trajectories with a close Io flyby before perijove, a close Ganymede before perijove flyby, or no satellite flyby. The Io trajectory case has a relative minimum in the total ΔV magnitude at 5.15 R_J (total $\Delta V = 990$ m/s versus 978 m/s at 1.02 R_J), while the Ganymede trajectory case has a relative minimum at about 12.4 R_J (total $\Delta V = 1002$ m/s versus 977 m/s at 1.02 R_J).

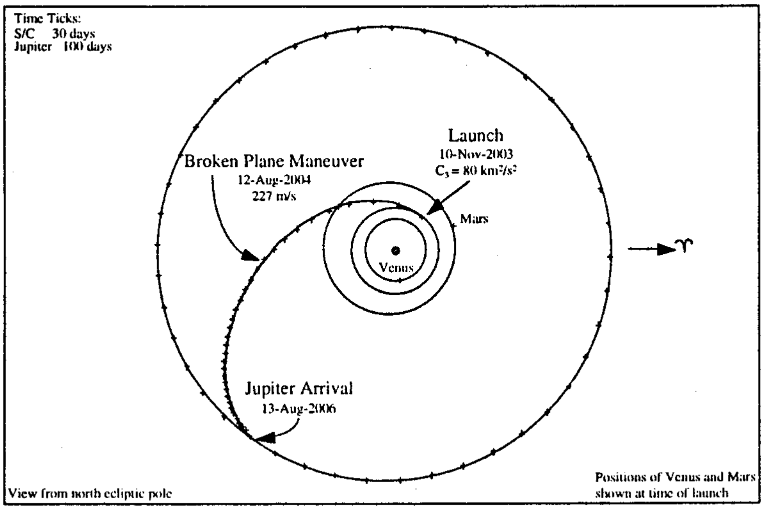


Figure 4. Europa Orbiter Direct Trajectory

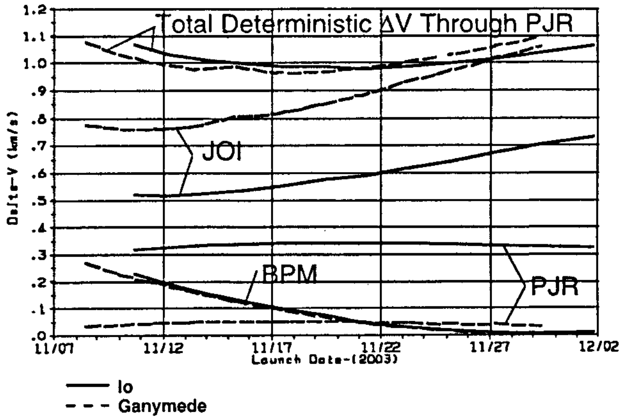


Figure 5. Deterministic ΔV for Optimal Launch/ Arrival Date Combinations - Io 500 km Alt, PJ-0 @ 5R_J; Ganymede 350 km Alt, PJ-0 @ 12.5 R_J

Figure 6 considered inbound flybys of Ganymede and Io at 500 km for a launch/arrival date close to the minimum (near the middle of launch/arrival periods). A Ganymede flyby performed at 350 km is nearly equivalent to an Io flyby at 500 km altitude (Figure 7). The new reference for the Europa Orbiter mission therefore became a trajectory with a Ganymede flyby at 350 km before JOI performed at a perijove of 12.5 R_J range. Figures 8 and 9 show the reference trajectory with the Ganymede flyby. For such a trajectory, ring plane crossing issues are completely avoided (Figure 10), the radiation dosage is only a few krad (lower by a factor of 10 or more), and the time-critical nature of performing JOI precisely at perijove is greatly alleviated. A gravity assist from Callisto on the outbound leg after JOI may be considered in the future but is not yet baselined.

Table 1. Deterministic ΔV Through PJR for Optimal Launch/Arrival Combinations (Ganymede Flyby)

Launch Date/(2003)	Arrival Date	BPM (m/s)	JOI (m/s)	PJR (m/s)	Total (m/s)
08-Nov	08-Jul-2006	267	776	34	1077
10-Nov	13-Aug-2006	227	762	40	1030
11-Nov	18-Sep-2006	193	759	46	998
13-Nov	23-Oct-2006	158	770	49	997
15-Nov	28-Nov-2006	126	809	52	986
17-Nov	03-Jan-2007	97	815	52	964
19-Nov	08-Feb-2007	71	846	51	968
21-Nov	15-Mar-2007	48	884	49	981
23-Nov	20-Apr-2007	29	928	46	1003
25-Nov	26-May-2007	15	969	43	1027
27-Nov	01-Jun-2007	6	1017	38	1060
29-Nov	05-Aug-2007	3	1063	34	1099

The perijove raise maneuver which targets to a Ganymede (G1) flyby is much smaller for a trajectory which has an initial perijove at 12.5 R_J rather than 1.02 R_J (61 m/s vs. 580 m/s). Varying PJR provides different conditions for starting the tour phase. Table 2 shows how the G1 V-infinity, perijove range and period after G1 vary for different PJR values.

Table 2. Tour Starting Conditions

PJR Magnitude (m/s)	G1 V_∞ (km/s)	Perijove1 Range (R_J)	Perijove1 Period (Days)
22	8.0	10.0	54.3
30	7.7	10.5	52.6
44	7.3	11.0	51.1
58	6.9	11.5	49.7
73	6.5	12.0	48.6
89	6.1	12.5	47.9
105	5.7	13.0	47.8

Tour/Endgame

A *Galileo*-like tour of the satellites Europa, Ganymede, and Callisto will begin with G1 (see Figure 11) and is nearly ballistic. It will take at least a year from arrival at Jupiter to get the spacecraft to the beginning of what is called the Endgame, which is the part of the trajectory during which the spacecraft will use only Europa flybys and large propulsive maneuvers to achieve the desired final approach to Europa (see Figure 12).

Initial work for early Europa Orbiter trajectory concepts was reported by Sweetser et al., upon which the current work is based.[12]

The formal guidelines for the tour/endgame phase of the Europa orbiter mission include minimizing the ΔV expended, keeping the total radiation dose to <2 Mrads (behind 100 mils Al), not exceeding 3 years between JOI and EOI, avoiding non-targeted flybys $<50{,}000$ km in range, avoiding multiple satellite flybys on the same orbit, avoiding encounters or maneuvers from 1 week prior to 2 weeks after the time when the Sun-Earth-Probe (SEP) angle is $< 5°$, and phasing the arrival at Europa such that the 30 day Europa orbital operations phase occurs ≤ 5 AU from Earth. As yet uninvestigated is how the final approach to Europa affects the range of subsequently possible orbit orientations (inclination and node) around Europa, but future work will clarify whether (and by how much) the tour/endgame is affected by such orientation constraints.

While the guidelines afford flexibility in designing the tour phase of the mission, the constraint of avoiding activities around solar conjunction and the requirement of having the orbital operations phase occur ≤ 5 AU from the Earth mean that the tour phase needs to be quite short for some launch/arrival date combinations and needs to be much longer for other launch/arrival dates.

As with *Galileo*, the first Ganymede flyby (G1) reduces period and is followed by a second Ganymede flyby (G2) to remove the inclination (about 5 degrees for the initial orbit). After the G2 flyby, the tour designer is free to choose a sequence of satellite encounters which will reduce the orbital period to about 3 Europa revs (10.5 days) while maintaining the perijove range above 8.8 R_J. (Lower perijove values will result in excessive radiation dosage.) When the perijove needs to be raised, a flyby of Callisto is often used. If the G1 starting conditions are near the bottom of Table 2, it is possible to continue satellite flybys which continue to pump down the size of the orbit.

The roughly half-dozen Europa flybys which constitute the Endgame will exhibit more or less the same spacecraft/Europa geometry because the spacecraft orbit will be in near-resonance with Europa's orbital period and therefore must encounter Europa at about the same point in its

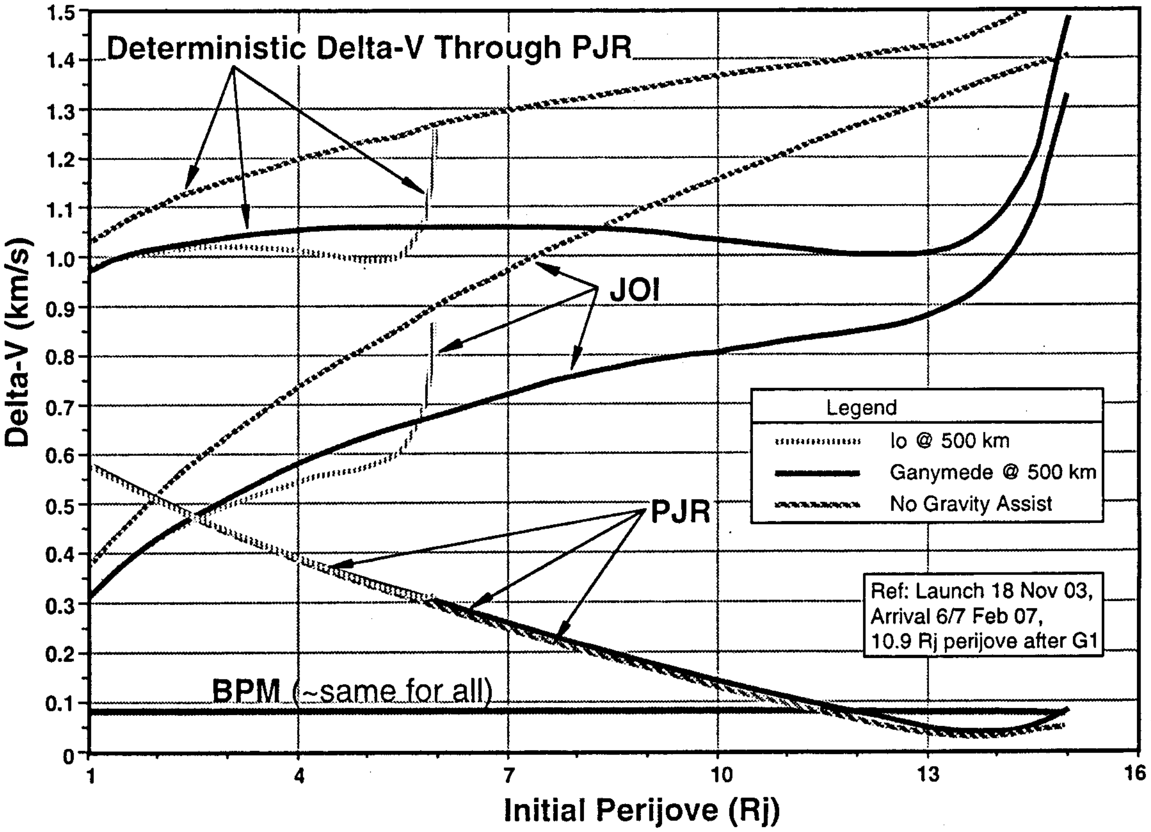


Figure 6. Deterministic ΔV Has Minima at 1, 5.15, and 12.4 R_J

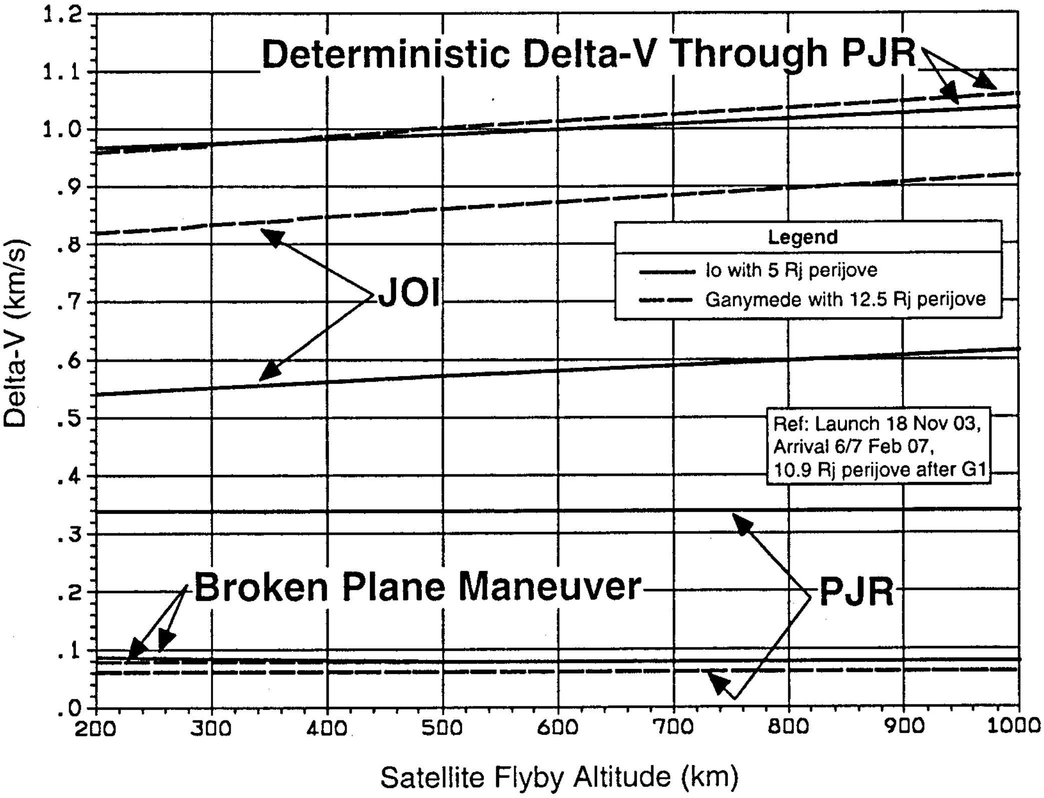


Figure 7. ΔV as Function of Satellite Flyby Altitudes

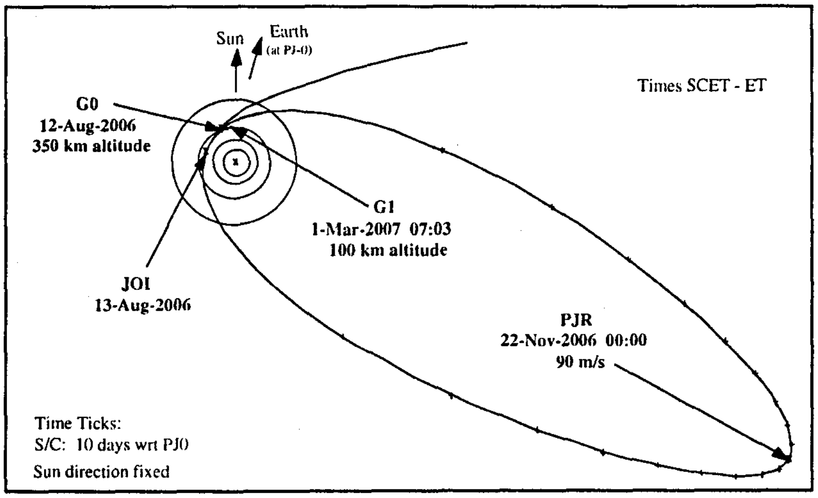


Figure 8. Initial Jupiter Orbit

orbit each time. The Endgame is expected to take about 3 months and culminates in a ballistic capture of the spacecraft by Europa. Preliminary estimates put the total radiation dose by the completion of the Endgame at about the limit of 2 Mrads, half of the mission total of 4 Mrads (behind 100 mils of Al), the other half coming during the 30 day primary mission around Europa.

During the Endgame, maneuvers at apojove are required to raise the perijove distance. When the spacecraft encounters Europa following such a perijove raise, its V-infinity will be lower than for the previous encounter. The flyby changes the resonance (ratio of the number of spacecraft revolutions about Jupiter to the number of Europa revolutions about Jupiter) to reduce the orbital period (see Figure 12).

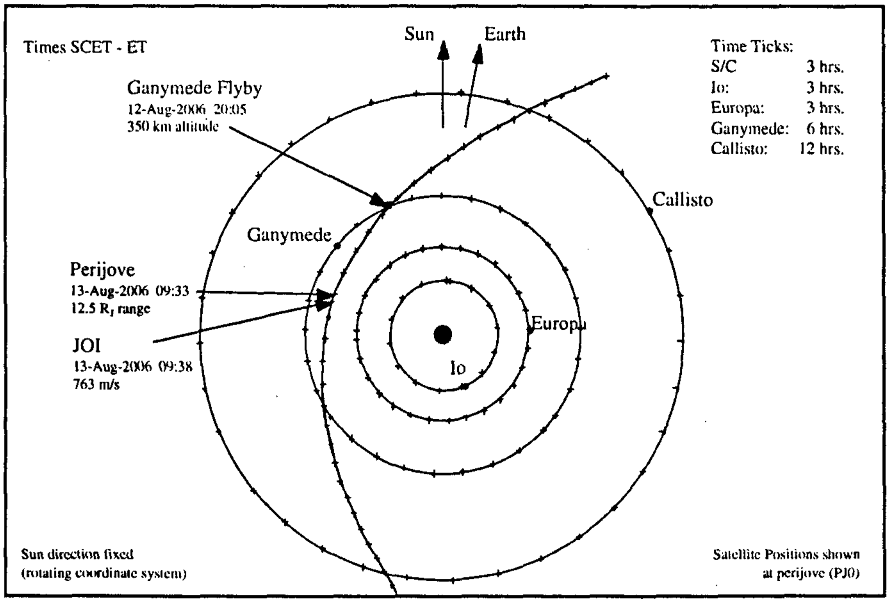


Figure 9. Arrival Day Geometry

After reaching a resonance of 5:6, two maneuvers are used before the next encounter to provide the conditions for capture of the spacecraft by Europa. One maneuver is at apojove and the other near the desired line of nodes. These maneuvers correct inclination and cause the spacecraft to be captured without cost into a highly elliptical orbit by taking advantage of Jupiter third-body effects. The capture orbit is unstable, however, and an energy reducing maneuver is required at periapsis to place the spacecraft in a stable orbit about Europa.

Current Status of Tour/Endgame

Mission design is currently at the stage of developing the end of the tour phase and designing the Endgame. The goal is to have a single integrated trajectory from launch through the start of Europa orbital operations. Previous work on the mission design involved pieces of the trajectory (launch to tour start, tour, and Endgame) which corresponded to different launch/arrival opportunities.

The Endgame has provided the most challenges. Previous work on the Endgame has been difficult because of convergence problems. It is unclear whether these difficulties are a result of nontargeted flybys or a shortcoming in the software.

Efforts have been expended to improve the software CATO (Computer Algorithm for Trajectory Optimization) by utilizing a nonlinear optimizer; however, it is not clear whether the upgraded software will solve the convergence problems, since the single Endgame case studied to date displays sensitivity to a non-targeted flyby of Ganymede at a range of 10,000 to 15,000 km.

Approaches to solving the convergence problem include: 1) trying to design the Endgame without close nontargeted flybys if possible, 2) incorporating additional control points (at perijoves) and breakpoints (at apojoves) on orbits with multiple spacecraft revs between encounters so as to allow maneuvers to occur at more natural locations, 3) incorporating multiple close encounters on a single orbit, and 4) obtaining convergence first with Ganymede made inactive as a perturbing body and then turning on the effect of Ganymede. This last approach has been successful when used by the programmer.

Future Tour/Endgame Work

Substantial work remains involving the tour and Endgame phases in order to obtain a complete integrated trajectory which satisfies the required orbit orientation (inclination, phase angle, line of nodes and apsides), and which stays within the total ΔV capability of 2500 m/s. A representative ΔV profile is shown in Table 3.

The feasibility of incorporating a second satellite flyby with Callisto outbound after JOI is yet to be studied. The appropriate geometry for Ganymede and Callisto repeats at 50 day intervals (7 Ganymede revs and 3 Callisto revs), so it might be possible to utilize a double satellite approach throughout the launch/arrival period. Navigation issues of a double satellite flyby also have yet to be studied.

Table 3. Representative ΔV Profile

	Main Engine	RCS	Total (m/s)
Interplanetary	115	4	119
JOI/PJR/Init orb	1006	4	1010
Tour	0	56	56
Endgame	590	19	609
EOI	578	2	579
Europa Ops	20	0	20
Reserve	84	20	104
Total by Phase (m/s)	**2393**	**105**	**2497**
Deterministic	2208	0	2208
Statistical	101	85	186
Reserve	84	20	104
Total by Type (m/s)	**2393**	**105**	**2497**

Much more work remains to be done to develop tours of different lengths so it will be possible to avoid solar conjunction and place the Europa orbital operations phase at a range of <5 AU from the Earth. Initially these constraints are being overlooked in an effort to get a converged trajectory from launch to the start of Europa orbital operations.

Navigation Issues

Preliminary navigation studies based on current mission assumptions indicate that radiometric data alone provide sufficient navigation performance to enable each phase of the mission.[13] The principal data type to be used is X-band range and Doppler tracking from DSN (Deep Space Network) stations. Optical navigation (OpNav) images of the Galilean satellites with stars in the background have been considered to supplement radiometric tracking in the Jupiter approach, tour, Endgame and Europa approach phases, but provided only small benefits over the radiometric-only solutions.

For the Jupiter approach phase study, the combination of OpNav and radiometric tracking reduced position uncertainties (mapped to the Jupiter encounter) by approximately 15% at 10 days from the encounter when compared to the radiometric-only case. These modest improvements in navigation accuracy offered by supplemental OpNav measurements are limited by the current camera design concept, which is geared towards a rather wide field-of-view to provide broad Europa coverage from fairly low orbit.

As described above, the Endgame phase of the mission is characterized by repeated Europa flybys and deterministic maneuvers culminating in the approach and orbit insertion around Europa. The relatively short durations (as short as ~1 day) between major trajectory events during the Endgame phase present a challenge to navigation and maneuver design strategy. The proposed utilization of ground automation (for orbit determination) and on-board automation (for maneuver design) in the navigation process will enable the reduction of both risk and ΔV in the Endgame phase. Figure 13 shows spacecraft position uncertainties mapped to Europa orbit insertion (EOI) based on an analysis of the latter part of a representative Endgame scenario. The two OpNav cases shown represent bounds on the expected navigation performance of the current narrow-angle camera design. The addition of OpNav images (one frame every 30 min) to the continuous radiometric tracking yields an improvement over the radiometric-only case, but it is evident that with an aggressive orbit determination strategy supported by ground automation, navigation utilizing radiometric data alone can be implemented to take advantage of the significant drop in orbit uncertainty at ~ EOI - 1.5 days.

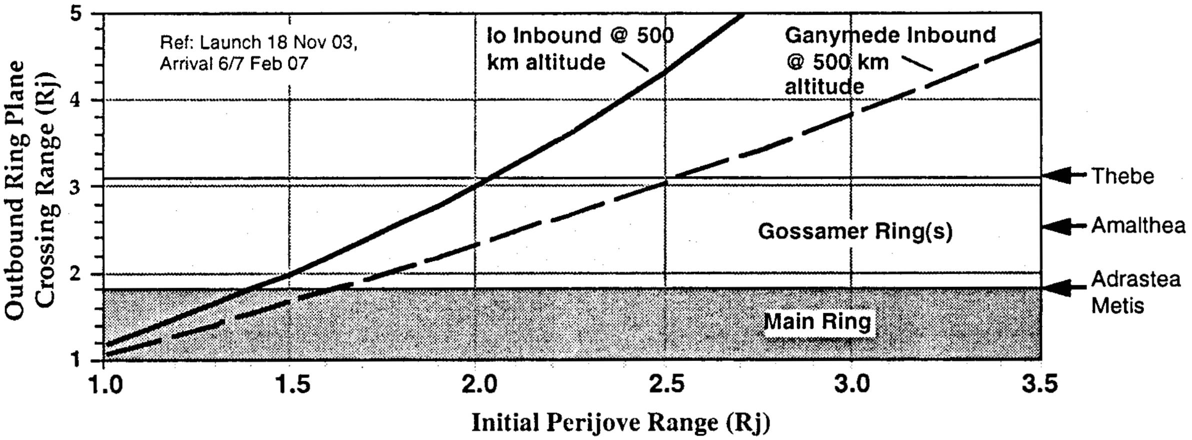


Figure 10. Outbound Ring Plane Crossing as Function of Initial Perijove Range

Europa Orbital Operations

Europa Orbit Insertion/Interim Orbit

A large burn, >500 m/s, will put the spacecraft into a low-eccentricity interim orbit from which the gravity field mapping experiment can begin (the current reference periapsis altitude is 200 km, although the actual value is subject to future analysis and negotiation). The eccentricity of the interim orbit around Europa, and the duration of stay in that orbit, will be dependent on orbit stability and gravity science studies that will be conducted in the Project's development phase. The gravity field mapping requires different orbits to help separate the small atmospheric effects from the gravity field signature and also the higher order gravity harmonics from each other.[14] By "walking down" the initial apoapsis it is believed that this gravity investigation requirement can be met at no significant additional ΔV cost (in fact it may reduce finite burn losses of the orbit insertion by segmenting it).

The large third-body forces from Jupiter

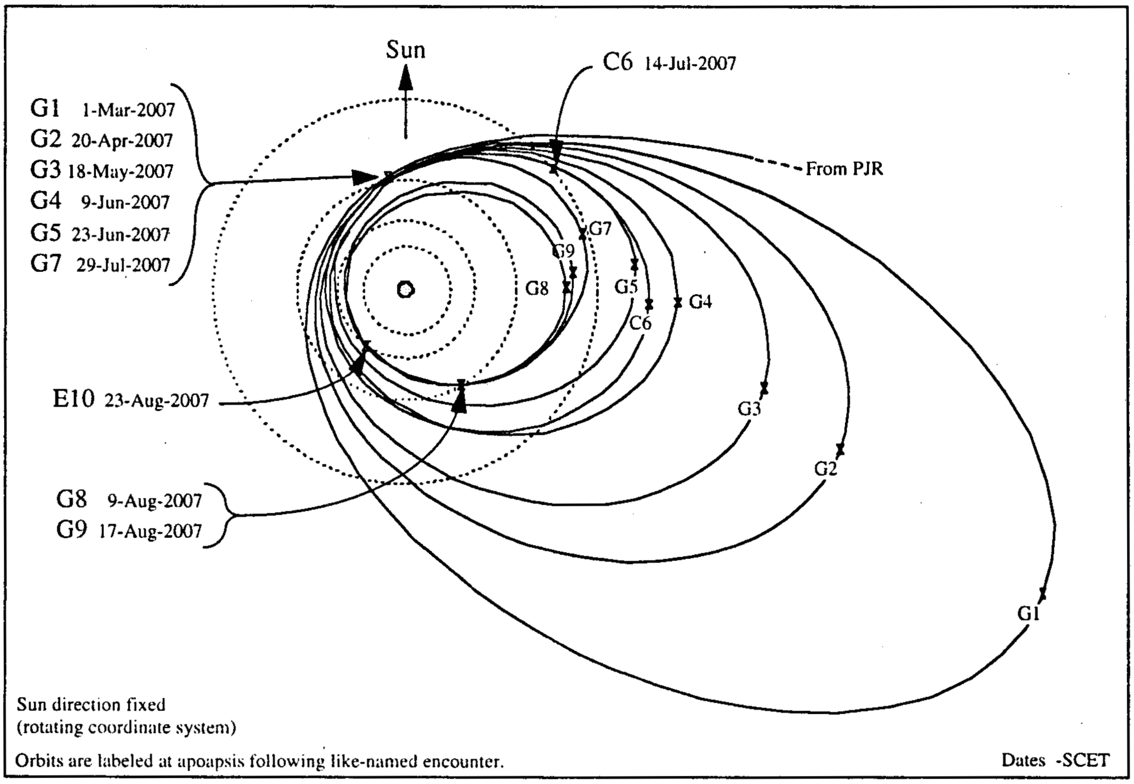


Figure 11. Galileo-like Tour

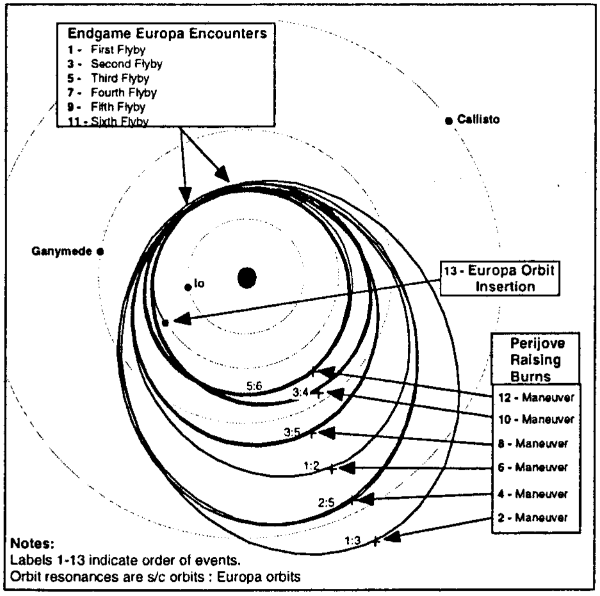


Figure 12. Endgame Trajectory Strategy

affect the stability of the spacecraft's interim orbit about Europa. For a given periapsis radius, orbit stability is primarily dependent on initial eccentricity, and is less sensitive to inclination, longitude of the ascending node and argument of periapsis. Figure 14 shows how the orbit lifetime varies with initial eccentricity; the data was generated assuming initial inclination and periapsis altitude of 75° and 200 km, respectively. Orbit lifetime is defined as the period of time it takes for the orbit to be perturbed to the point where the radius of closest approach is less than Europa's surface radius, assuming no spacecraft orbit maintenance is performed. Orbit lifetime is longest (> 50 days) for initially circular orbits, and is close to 10 days as the initial eccentricity approaches 0.1.

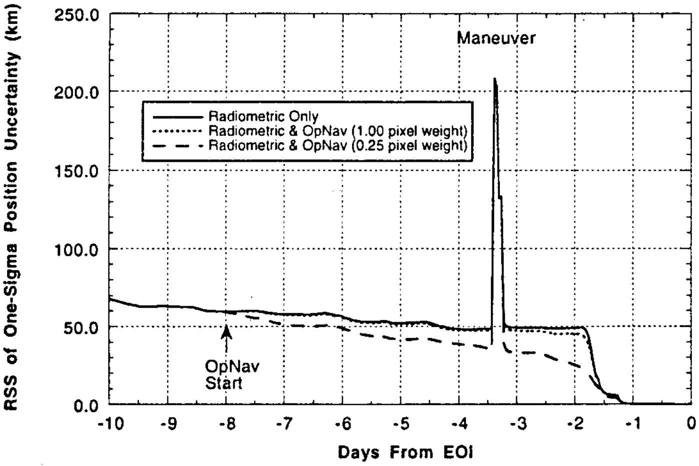


Figure 13. Orbit Uncertainties Mapped to EOI for Reference Endgame

There is no specific allocation of ΔV for an altitude change once in close Europa orbit although 20 m/s is allocated for altitude control over the 30 day mission.

Table 4 includes a summary of the range of key parameters describing the final mapping orbit around Europa. The upper limit on altitude is set by the altimetry investigation, the lower limit is not as well characterized but will be driven by global coverage requirements and orbital safety. The lower limit on inclination is driven by the desire of all investigations to globally sample Europa while the upper limit is set by the desire of the gravity investigation to have at least 10 degrees of apparent orbit plane precession during the 30 day orbital mission. The orbit orientation with respect to Earth is driven by the radio-tracking desire that the orbit not be near edge- or face-on and with respect to the Sun for imaging. Significant eccentricity in the final orbit will degrade coverage and resolution, in some combination, for all the investigations.

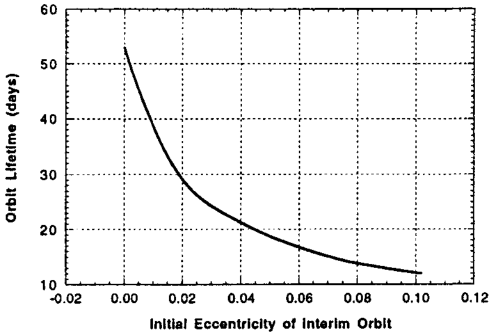


Figure 14. Eccentricity Drives Interim Orbit Stability

After the appropriate length stay in the initial eccentric orbit, the spacecraft will circularize its orbit at 100-200 km altitude (as indicated above, 200 km is the current reference; future studies will determine the final altitude).

Sample Scenario

Figure 15 shows one example of how the orbital operations may be conducted in Europan orbit. It is important to note that the chosen science team is expected to be intimately involved in the design of the actual orbital operations, and the profile may vary dramatically from that shown here, however, the example is consistent with meeting the 1A science objectives and is within the scope of the

Table 4. Range of Potential Europa Final Mapping Orbit Parameters

Parameter	Reference	Likely Range
Altitude	200 km	100-200 km
Period	138 min	126-138 min
Inclination	83°	70-88°
Line of Nodes	Ascending node - 310° (see note 1)	• 10°< Earth/Europa/Node angle<80° • Within 20-50° of solar meridian
Eccentricity	0	0 - 0.1

NOTE 1: Defined here as the angle measured clockwise from the solar meridian when viewing southward (from Europa's north pole) to the spacecraft's ascending node.

available resources. Additionally, some key constraints that must be observed in the actual sequence are accommodated in the example. The most important of these is that there is not sufficient power to operate all of the instruments simultaneously. Another geometrical consideration illustrated in the example is the once per eurosol (Europan day) eclipse and Earth occultation by Jupiter lasting as much as 3.5 hours. Not shown are the up to 50 minute eclipses and Earth occultations of the spacecraft by Europa that will occur every spacecraft orbit around Europa.

It is envisioned that the interim orbit will provide an opportunity for initial characterization and initial orbital science from all instruments. A TBD duty cycle of nadir-pointed data acquisition and Earth-pointed data downlink will take place during the interim orbit.

A navigation analysis performed for the Europa orbital operations phase of the mission has shown that several days of continuous tracking is important early in the phase to achieve adequate characterization of the gravity field of Europa. Certain low degree/order gravity field coefficients (J_2 and C_{22}) were estimated during the Galileo mission, but a more accurate determination of these and higher degree/order terms is an objective for Europa Orbiter. The choice of 200 km for the reference mission was, in part, driven by the issue of spacecraft orbital safety in the critical early phase of the orbital operations. The study also identified trade-offs existing between orbit determination accuracy and the frequency and magnitude of unbalanced attitude turns. The impact of unbalanced attitude turns on navigation is greatest whenever the spacecraft dynamics must be mod-

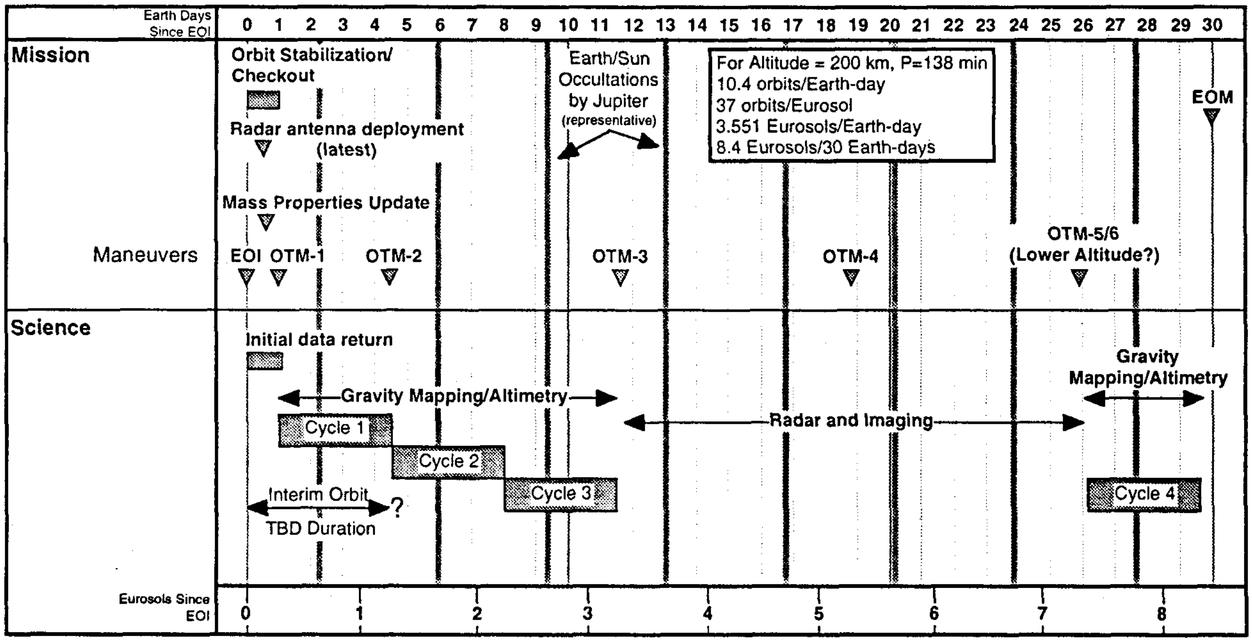


Figure 15. Sample Europa Orbital Operations Scenario

eled accurately, such as during the gravity field determination phase. The current spacecraft and mission design strategy is to minimize these non-gravitational forces by implementing balanced thrusters in concert with a gravity-gradient-stable attitude or reaction wheels for attitude control.

Gravity/Altimetry Phase

Following circularization into the mapping orbit, the mission will enter the gravity /altimetry phase for two eurosols. A preliminary 36:1 duty cycle between nadir-pointed orbits to Earth-pointed downlink orbits is planned during this phase, during which the MGA will be the primary method of acquiring tracking data while nadir-pointed. This duty cycle is primarily driven by the desire to maximize tracking time and the desire to minimize non-gravitational forces on the spacecraft that might be associated with turning the spacecraft.

Radar/Imaging Phase

The radar/imaging phase of the mission follows the gravity/altimetry phase and will take about 4 eurosols to complete at the expected duty cycle of 2:8 between nadir-pointed orbits to Earth-pointed downlink orbits. This average duty cycle is driven primarily by downlink capability. It is expected that the spacecraft transmitter will be turned off during the nadir-pointed science data gathering orbits of this phase to allow sufficient power to be available for the instruments.

If there is sufficient propellant left after the radar/imaging phase, an orbit altitude lowering may be possible to enable selected high-resolution data taking for all investigations. There are no current plans for any extended mission operations.

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